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Mitigation of Concurrent Flood and Drought Risks Through Land Modifications: Potential and Perspectives of Land Users

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Abstract

Modifications to land can serve to jointly reduce risks of floods and droughts to people and to ecosystems. Whether land modifications are implemented will depend on the willingness and ability of a diversity of actors. This article reviews the state of knowledge on land modification use in areas exposed to dual hydrologic risks and the land owners, managers, and users who directly make decisions about action on lands they control. The review presents a typology of land modifications and explains how land modifications interact with the hydrological cycle to reduce risks. It then addresses the roles and perspectives of the land owners, managers, and users undertaking land modifications, summarizing theories explaining motivations for, as well as barriers to and enablers of, land modification implementation. The analysis reveals geographical differences in narratives on land modifications as well as knowledge gaps regarding variation across actors and types of land modifications.

Contents

1. INTRODUCTION

Although climate change is often discussed as leading to either a decrease or an increase in precipitation, in many regions of the world, climate change is concurrently increasing the frequency and magnitude of both floods and droughts (1). The extent to which this hydrologic change translates into increased risks to people and to ecosystems will be moderated by how land is managed and used, particularly at the local or watershed scale. For example, intensively managed land with degraded ecosystem functioning intensifies hydroclimatic risks, and restoration and adaptation practices that revitalize ecosystems or provide new ecosystem services may serve to mitigate hydrological extremes (2). Changes in how land is managed and used can serve to mitigate the negative effects of hydroclimatic extremes as well as of hydrologic variability (3).

Land modifications refer to intentional human interventions in land characteristics, use, and/or management practices that affect the hydrologic cycle and, in doing so doing, alleviate the negative impacts of climate change. Land modifications include both actions that alter the land in new ways and actions that attempt to restore the land to a more natural state. Land modifications vary in the extent of the expertise, resources, and tools needed to implement them, as well as the spatial area needed for them to be effective. Some land modifications are synergistic with existing land use and management (4), whereas others may require changes to or even discontinuation of existing practices (5, 6).

Land modification: an intentional human intervention in land characteristics, use, and/or management practices that affects the hydrologic cycle and alleviates the negative impacts of climate change

Although land modifications can be adopted to address either floods or droughts, a benefit of many land modifications is their ability to concurrently address both types of hydroclimatic risks (7). This characteristic is notable, given the potential for "tradeoffs in risk reduction between floods and droughts" (7, p. 81; see also 8) and that floods preceded by droughts have more pronounced impacts or require greater risk reduction than independently occurring events (9, 10).

While land modifications can serve as a valuable tool for responding to climate change, critical questions remain regarding the extent to which they will be adopted as well as whether they can and will be implemented at the scale needed to provide benefits at the watershed level and beyond. Authority over land, and thus the decision to implement land modifications, is spread, and at times shared, across a variety of actors (11). Some land is publicly owned, yet a substantial portion of the world's land is privately owned. While governmental laws and policies can regulate or otherwise seek to influence how private lands are used and managed, implementation of land modifications is often contingent on the interest and ability, and sometimes compliance, of those who own, manage, and/or use land (12, 13). Uptake of land modifications is further complicated because land is often managed on a parcel-by-parcel basis; thus, coordination may be needed across parcels and within a watershed (14).

In light of this distributed control over land, many public policies and programs, as well as scholarly work on adaptation to hydroclimatic risks, have focused on integrated watershed-level planning (see, e.g., 15, 16) and other approaches through which public agencies and policy-makers increasingly look to engage citizens in adaptative action (17). Public agencies are also increasingly devolving responsibility for disaster security, including flood and drought risk management, to private landowners (18). Yet landowner, manager, and user response has been mixed, with some instances of regional planning initiatives struggling to convince landowners to uptake land modifications and other instances of landowners autonomously deciding to implement them (19). These trends highlight the need to develop greater understanding of how the owners, managers, and users with direct control over the land perceive land modifications; their motivations; and their barriers to and enablers of their adoption of land modifications, as well as variation across differing groups of owners, managers, and users. This knowledge is needed both to develop policy interventions that encourage or incentivize actions and to predict where and to what extent land modifications might be deployed.

Barrier: a real or perceived obstacle/constraint impeding the land modification that can be overcome

Enabler: an external intervention that can help to overcome barriers and otherwise support land modification implementation

Scaling-up: process of more widely deploying land modifications by increasing either the size or the number of land modifications implemented in a region

To address this knowledge gap, in this article, we review the academic literature on land modifications and the land owners, managers, and users who undertake those modifications for the purpose of mitigating the intermittent occurrence of both floods and droughts. Our focus is on research that examines areas exposed to both flood and drought risks in a response to growing awareness of the need for integrating flood and drought risk reduction strategies and for improving knowledge of how human decision-making is influenced by interactions and feedbacks between hazards (8).

We begin with a description of the fields relevant to land modifications and the types of research and knowledge that have been produced on the topics in recent years. Following this summary, in Section 3 we describe the linkages and feedbacks between land and hydroclimatic risks in more detail, delineating a typology of land modifications based on the nature of the modifications made and how the modification interacts with the hydrologic cycle. In Sections 4 and 5, respectively, we address the question of who makes decisions regarding and the motivations, enablers, and barriers to deployment of land modifications. In Section 6, we examine the assessment of land modifications along with the potential for scaling-up. Finally, in Section 7 we evaluate the state of knowledge on land modifications, describing critical gaps in knowledge, including theorizing human behavior, addressing differences across groups of land owners, managers, and users, and accounting for differences in how risks and solutions are framed across geographies.

2. STATE OF THE LITERATURE ON LAND MODIFICATIONS

Land modifications have been addressed within a broad set of research agendas, including those focused on sustainable land management (see, e.g., 2), natural flood management (see, e.g., 6, 11), ecosystems-based adaptation (see, e.g., 20), and adaptation to climate change (see, e.g., 21, 22), among others. Within these research agendas, varying aspects of land modifications are captured by differing disciplines. The physical aspects of interactions between land and hydrology are examined through research drawing on climate science, hydrology, geology, civil engineering, and ecology; the social dimensions related to people, decisions, and barriers/facilitators are studied using theories and methods drawing on economics, political science, psychology, sociology, public policy and administration, and human geography. As a result, literature on land modifications is spread across a large variety of publications, and discussions on the topic span multiple venues.

To synthesize this literature and determine the state of knowledge on land modifications, we adopted a two-pronged approach that combined a systematic review of literature explicitly connected to land modifications with a targeted review of research well recognized as addressing land in the context of environmental behavior or climate adaptation. The systematic review identified all records of papers published between 1979 and 2021 located in Web of Science and Scopus that result from a keyword search. As the focus of the review is on multifunctional land modifications that serve to concurrently mitigate hydrologic risks at both ends of the spectrum, search terms included the requirement that the papers reflected exposure to both extremes (e.g., FLOOD and DROUGHT). Additional requirements were that the papers reference land (LAND or PROPERTY), action on the land (RETENTION or ADAPTATION or ADJUSTMENT or RECHARGE or HARVESTING or RESTORATION or ACCOMMODATION or CHANGE), and actors (OWNER* or MANAGER* or USER* or HOUSEHOLD* or HOMEOWNER* or LANDHOLDER* or FORESTER* or FARMER*). Due to the review's focus on actors with the direct power to undertake action on a specific parcel of land, keyword search terms do not explicitly encompass higher-level authorities (e.g., watershed organizations, irrigation districts, or governmental agencies); however, papers addressing those entities are not excluded from the search so long as the paper also addresses either individuals or collectives that directly control the parcel of land.

These search terms resulted in an initial list of 887 records, which were then screened for duplicates. Abstracts were reviewed to confirm the paper indeed addressed both land modifications for the concurrent mitigation of the risks of floods and droughts and the behavior of land owners, managers, or users who make decisions about that land. Ninety-three papers met the review criteria. The **Supplemental Appendix** provides more information on keywords, selection criteria, and the screening process and outcomes.

Supplemental Material >

The literature identified through this review spans the globe, albeit with an uneven geographic focus. Most papers address a single location within a single region, although a few papers (4%) covered countries on two different continents. The majority of papers examine either Asia (44%) or Africa (35%), with many fewer papers examining North America (13%), South America (6%), Australia (4%), and Europe (2%). The dominant focus of research on land modifications in Asia and Africa is small-scale (subsistence) farmers, whereas research in North America and Australia addresses a broader range of land owner, manager, and user types, including communal schemes, private companies, and nonagricultural users. Due to the narrow geographic focus of most papers, little comparison exists across social and/or ecological contexts for land modifications.

Papers identified as part of the systematic review are diverse in their scope and objectives. A majority aim to study adaptation to climate change broadly, with land modifications included in the research as one among many options for responding to risks. For example, 41% of papers evaluate an individual's knowledge of climate and perceptions on risks, 32% investigate perceived barriers to adaptation, 18% study socioeconomic or demographic factors affecting adaptive behavior of an individual or a household, and 8% explore how land tenure affects vulnerability to climate change. Although these papers provide insights on land owner, manager, and user behavior, in many, details on motivations to undertake land modifications are sparse (see Section 5.1). Other papers, albeit a smaller percentage of them, engage more in depth with land modifications. For example, 25% of papers evaluate physical or economic benefits of land modifications, 23% estimate the impacts of climate change, often with computer modeling, and 7% aim to build macromodels of agricultural production changes that include land modifications. Less than 10% of papers measure the physical extent of modifications undertaken. These findings indicate that the literature on the key decision-makers of land modification in relation to concurrent hydroclimatic hazards is far from complete; in depth studies that examine motivations in relation to specific land modifications and their expected effects in addressing both flood and drought risks are sparse and comparisons are lacking.

In addition to the scholarly work identified by the systematic review, knowledge relevant to the uptake and deployment of land modifications to address hydroclimatic risks can also be found in research not specifically focused on, yet applicable to, land modifications. This includes literature on adaptive/risk-reducing behavior in response to climate change, on environmental behavior of land owners, and on ecosystems or nature-based adaptation (see, e.g., 23–25, among others). Papers identified in the systematic review do not delve in depth into the science of land modifications, contain a paucity of comparative studies, and only rarely theorize behavior. As such, we draw on this complementary literature to provide a more comprehensive explanation of land modifications as well as to identify potential areas in which knowledge from research on behavior could be constructively applied to land modifications. Literature included for this purpose was identified through a selective search method (see, e.g., 26) that focused on finding seminal works or highly cited references from top-ranked journals and/or review articles on the topic.

3. LAND MODIFICATION TYPOLOGY/CATEGORIES

Climate, the hydrologic cycle, and land are deeply interrelated; changes to one have effects on the others. Rising temperatures lead to increased evaporation, an increase in the amount of moisture that can be held in the atmosphere, and shifts in atmospheric circulation patterns (1). These changes in turn affect the timing, intensity, frequency, and duration of precipitation (27). The magnitude of these changes, as well as their effects, is influenced by land use and management. Evaporation, run-off, and infiltration are mediated by land cover, soil moisture, topographic, and subsurface conditions (28, 29). Impervious surfaces increase runoff (30) and water infiltration decreases when land is left bare (31). In contrast, grasses and vegetation with continuous root systems can increase infiltration, reducing overland flow and the potential for flooding (32). Soil and rock heterogeneity, soil compaction, fissures and fractures, and the architecture of current and/or decayed root systems also affect how and where water flows (33). Furthermore, the water retention capacity of the landscape is reduced and runoff is increased by river channel straightening, wetland drainage, and disconnection of rivers from their floodplains (34).

People can intervene in these hydroclimatic processes by making changes to their properties. Land modifications take many forms (see **Figure 1**), each of which contributes to mitigating the effects of floods and droughts in different ways. Land modifications that serve to address the concurrent risks of floods and droughts do so by slowing and/or infiltrating water during periods of high precipitation such that water remains available in soil or storage longer, aiding with potentially extended periods of low precipitation. Modifications to land cover affect the perviousness of the land as well as evapotranspiration. Changes to soil structure and composition can facilitate infiltration and water retention. Alterations to topography can slow or speed runoff and infiltration. Shifts in land management practices (cropping and livestock) and land use serve to change not only land cover, soil structure/composition, and topography but also the negative effects of too little or too much water on production (35, 36). Most land modifications are not mutually exclusive and which form(s) of modification are used will depend on the objectives and capabilities of the person(s) seeking to make the change.

The scale at which land modifications are implemented will affect whether the modifications have property-level, localized, and/or watershed effects. In general, modifications that extend

Land cover alterations

Description: Changes to the (bio)physical surface cover of land to reduce evaporation, increase water infiltration and/or retention capacity, and/or slow outflows

Example: Wetland restoration, hedge rows, tree planting, buffer vegetation strips

(see, e.g., Belle et al. 2018, McCarthy et al. 2021, Oyekale & Oyekale 2019)

Soil enhancements

Description: Changes to soil quality and structure to enhance infiltration, water retention, and other properties of soil

Example: Mulching, reduced tillage, biochar, manure and soil additions, intercropping, clay-busting crops, agroforestry

(see, e.g., Akinyi et al. 2021, Kalele et al. 2021, Nguyen & Hens 2021)

Topographic alterations

Description: Changes to the land elevation and slope that affect rates of water flow across the landscape

Example: Terraces, wetlands construction, floodplain reconnection, silt pits

(see, e.g., Abubakar et at. 2021, Arora & Birwal 2017, Gooden & Pritzlaff 2021)

Water capture and storage

Description: Creation of spaces that accumulate water as it falls or runs off and retains that water for an extended period of time

Example: Water spreading weirs, rainwater tanks, swales, channels, dams

(see, e.g., Amede et al. 2020, Castonguay et al. 2018, Gawai & Sen 2016)

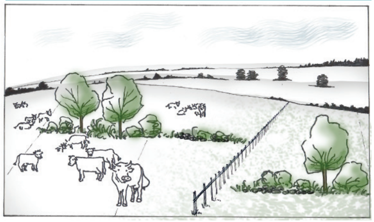
Cropping alterations

Description: Changes to crops, cropping patterns, and cropping systems to reduce water consumption and to increase infiltration of water to the aquifer

Example: Crop diversification, crop rotation, double cropping, changed planting and harvesting times, bed sowing, embankment of fields

(see, e.g., Choosuk et al. 2021, Khanal et al. 2018, Tessema & Simane 2021)

Livestock alterations

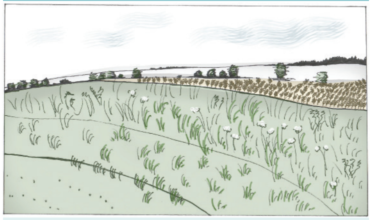


Description: Changes in species raised, pasture, grazing patterns, and sheltering of livestock to reduce erosion and soil compaction and/or address livestock susceptibility to floods and droughts

Example: Pasture rotation, altered mobility patterns, reductions in stocking rates, fodder storage modifications, improved shelters, integrated crop-livestock systems

(see, e.g., Amede et al. 2020, Rao et al. 2016, Rolfe et al. 2021)

Conversion of land use



Description: Switching from one land use to another

Example: Relocating from floodplains, reduction or abandonment of agricultural production, shifting from livestock to crop production, agroforestry

(see, e.g., Ali et al. 2020, Ayeb-Karlsson et al. 2016, Mahaarcha 2019)

(Caption appears on following page)

Figure 1 (*Figure appears on preceding page*)

Categories of land modifications for mitigating hydroclimatic risks**.** Drawings with permission from Reference 56. Examples and respective citations include land cover alterations: 5, 37, 38 (Belle et al. 2018, McCarthy et al. 2021, Oyekale & Oyekale 2019); soil enhancements: 39–41 (Akinyi et al. 2021, Nguyen & Hens 2021, Kalele et al. 2021); topographic alterations: 42–44 (Abubakar et al. 2021, Arora & Birwal 2017, Gooden & Pritzlaff 2021); water capture and storage: 45–47 (Amede et al. 2020, Castonguay et al. 2018, Gawai & Sen 2016); cropping alterations: 48–50 (Tessema & Simane 2021, Choosuk et al. 2021, Khanal et al. 2018); livestock alterations: 45, 51, 52 (Amede et al. 2020, Rolfe et al. 2021, Rao et al. 2016); conversion of land use: 53–55 (Ali et al. 2020, Mahaarcha 2019, Ayeb-Karlsson et al. 2016).

across a larger spatial area will have a greater influence on flows and storage of water (57). However, the specific hydrogeologic context, such as the presence of fissures or faults or the location of the modification within the watershed, will influence the degree to which the modification alters hydrologic flows (6).

Land modifications provide both private benefits to the entities that implemented them as well as public benefits to a broader set of entities within the watershed. These benefits include not only mitigation of floods and droughts but also biodiversity enhancement, improved ecosystem functioning, and economic value (2). For example, at the individual level, agroforestry mitigates localized effects of floods/droughts on soil conditions, serves to diversify income (cash crops, fruit trees), and supports adaptation to increasing temperatures (shade from trees to reduce heat) in both humid (58) and semiarid areas (59). At the watershed level, agroforestry promotes advanced root systems and deeper soils that retain more water and reduce runoff (60). At the regional or global level, agroforestry enhances carbon storage and biodiversity (2, 61).

4. ROLES AND PERSPECTIVES OF LAND OWNERS, MANAGERS, AND USERS

Whether, and which, land modifications are adopted will depend on the owners, managers, and users of the land (12, 19). A land owner is an individual or entity having legal title of the land, which enables them to undertake different types of activities on the land, to sell it or lease it, and to enjoy the benefits derived from their management and use of the land. A land manager is an individual or entity designated by the land owner to administer or control the use of land. A land manager may be an individual administrating different land uses for one large landowner (as an employee) or may be a company managing land leased from a large number of small landowners (as a tenant). A land user is any person or entity that actually uses the land, be that as an owner, manager, renter/tenant, or occupier. Landowners may also serve as land managers and users, for example, a small single family farm.

Systems for land tenure (the legal regime for ownership or holding of land), and consequently relations among land owners, managers, and users, differ enormously from country to country. Land tenure and use is strongly embedded in the history of human settlements and the evolution of government in a region. In many locations around the world, the land tenure is unclear—due to contested claims, overlap between traditional and colonial regimes, or changes in systems of governance (62–64). For example, in Uganda approximately 20% of land is burdened with overlapping property rights between registered owners and legally recognized unregistered occupants (65). In Cameroon, the state serves as the guardian of all lands and does not recognize many of the customary land rights from the precolonial era. Issued formal land titles are scarce and poorly enforced, so the incentives to formalize property titles are low (66). A lack of clarity about land titles increases the vulnerability of land users to climate change and results in further land degradation (2, 64).

Land user: any person or entity who modifies, takes action on or otherwise derives benefits from land

Land tenure is important because land owners, managers, and users vary in how they perceive and how they are affected by increasing hydrological risks. Land owners with secure tenure have a greater incentive to invest in, make improvements to, and protect property because any long-term benefits of such actions accrue to them (64, 67). Due to their shorter time horizons, managers or renters may be less aware of hydrologic risks and/or may need to see immediate returns on their actions in order to justify investments (63). For example, experiments with Argentinean farmers showed that "the same individual focuses on enhancing the value of owned land, but on maximizing returns from rented land" (68, p. 162). Research in Fiji similarly demonstrated that fields with a maximum 5-year lease contract produced significantly lower sugarcane yields than fields under longer leases or ownership (69).

There is heterogeneity even among the categories of land owners, managers, and users. Each can include private actors (varying from individuals to businesses of different size and legal status), public entities (representing interests of local, regional, or national governments), and formally established quasi-private or quasi-public entities contributing to land conservation and restoration goals [such as land trusts and other types of nongovernmental organizations (70)]. This distinction is important because, as described below, public and nonpublic landowners likely vary in their adaptation goals as well as capacities. In large parts of the Global South, there are also communal land users (71), whose behavior is complicated by the need to coordinate and make joint decisions among co-owners. This diversity of actors needs to be accounted for in both research on and policies seeking to influence uptake of land modifications.

Private entities are often concerned with deriving benefits from the land, such as livelihood sustainability (individuals) or economic viability/gain (businesses). They generally focused on adaptation actions that provide private benefits, i.e., those that accrue directly back to themselves. However, as private entities are embedded within the local society, they may also be interested in adaptations that provide public benefits, i.e., those that accrue to the broader community or watershed (see, e.g., 72). For example, private actors have been documented as undertaking land modifications that vary from maladaptation practices such as deforestation (73), actions affecting outputs from the land, such as crop changes (74), and land modifications that provide both private and public benefits, such as retention pond restorations (75).

The actions of quasi-public or quasi-private entities are determined by their declared goals and sources of funding, consisting of private donations and/or public sector contributions. These organizations often focus on delivering public benefits from land management and use. The land modifications they adopt tend to focus on environmental measures that include changes to land topography or land cover, such as wetland restorations [e.g., The Wetland Trust, The Nature Conservancy (**https://www.nature.org/en-us/what-we-do/our-insights/reports/**)], river restorations, and tree planting [e.g., The River Trust (**https://theriverstrust.org/**), Trees for the Future (**https://trees.org/2030-2/**)].

Communal land owners, managers, and users have characteristics parallel to those of both private and public entities. While they exist around the world, they often are located in countries with unclear or overlapping land tenure systems (62, 65). A driving concern is often sustainability of the livelihood of co-owners; co-owners may differ in perspectives as to how to best respond to hydroclimatic risks, and research provides evidence of both successful adaptation by communal property regimes and conflicting situations (63). An example of the former occurred in Japan, where agricultural communities that communally managed lands developed risk and flood damage sharing mechanisms that included joint soil and crop land modifications in order to secure the livelihoods of all community members regardless of a community member's location (76). An example of the latter occurred in the Eastern Ethiopian rangelands, where pastoralists were forced to migrate elsewhere because the land they used was appropriated by others investing in the land productivity through construction of irrigation channels or dams (45).

Public entities (municipalities, states) have dual roles in influencing land use/management and adoption of land modifications. On one hand, they create and implement public policies that prohibit or encourage certain land uses within their jurisdictions, be those publicly, privately, or communally held lands. Here we focus on their role as land owners, managers, or users in the instances when they have direct control over parcels of land. In comparison with private actor motivations, land modification decision-making processes of public entities are rarely investigated (77). In making decisions, public entities must contend with political pressures, balancing different competing interests (11, 78). Coordination across multiple concurrent policy goals (such as agricultural viability, water supply security, biodiversity enhancement, natural risk mitigation) is challenging. Public officers/managers also have to navigate complex institutional processes that slow down actions (79) and limited public funds (80). These factors hinder adoption of multifunctional or more sustainable land uses (11, 19), including adoption of land modifications. For example, evidence from the Czech Republic suggests that at the local level, public representatives tend to avoid unpopular land decisions, such as land modifications that limit use of municipal lands or land-use plans that restrict development to mitigate future flood damages (81).

In addition to the characteristics of decision-maker, attributes of the land itself—including current use, where in catchment it is located, and plot size, among other attributes—affect the willingness and ability to adopt different land modifications. The flexibility to make modifications on land used for productive use, such as farming or forestry, will depend on how land modifications affect current production and whether the land is essential to livelihoods (2, 20). A high dependence on the current land use and few options for livelihood diversification constrain the potential for modifications (82). Implementation of land modifications might be limited by rigidity of land use regulation. Particularly in the Global North, regulations may prevent conversions between fields, forests, and restored ecosystems (such as wetlands) or may not support multifunctional land uses, such as agroforestry (83). Furthermore, the location of land within the catchment and of the modification within the plot matters, particularly for water capture and storage and land topography modifications. Floodwater storage areas upstream mitigate risk for downstream settlements (4, 84). Infiltration and groundwater recharge need to be undertaken in locations with suitable subsurface hydrogeologies (85). Contrarily, soil, crop, and livestock modification effects seem to be much less dependent on the plot location (86, 87). Consequently, geography is a key determinant of which types of modifications are suitable for a given plot as well as where the benefits of deployment are experienced and who accrues them. In addition, fragmentation of land ownership/use (large number of small plots) may negatively affect the implementation of land modifications, especially those that require coordination among neighboring land users, such as river channel restorations (88).

Finally, adaptive capacity of land owners, managers, and users is a key variable influencing both vulnerability and uptake of land modifications (89, 90). Adaptive capacity refers to the potential or ability of an individual or a community to cope with, adapt to, or recover from the negative impacts (91). Adaptive capacity is affected by available resources, knowledge, and social capital (92, 93). For example, wealthier land owners, managers, and users in Thailand are able to invest in a broader range of land modifications (49). In the Himalayan mountains, farmers with "strong market linkages, greater assets, larger family and livestock size *are more* capable of 'stepping-up' and adapt to changes" (94, p. 9). Similarly, in Pakistan small subsistence farmers lacking financial resources and market access are less able to respond to the effects of climate change (95).

With respect to scholarly knowledge, our systematic review of papers that address both land modifications and the people who choose to implement them indicates the emphasis of research is on rural, private, and agricultural land users located primarily in the Global South, and the private benefits of land modifications to them. The vast majority (81%) of papers examine land modifications in rural areas, with few (6% of papers) examining land modifications in urban areas, and the remaining (14% of papers) either spanning both rural and urban areas or not specifying the geographic context. The use of land modifications to address dual flood and drought risks likely receives less attention in urban areas because they frequently rely on water supplies from beyond city limits, and thus modifications to address supply would be located outside the city. In the urban environment, land modifications for dual risk mitigation entails, e.g., the use of garden plots for rainwater harvesting (46) or modifications of urban agriculture practices (96).

In terms of who is making land modifications, 63% of papers examine small land holders (individuals or households) engaged in agricultural production that rely at least partly on that production for subsistence. Approximately 42% of papers include farmers or farming companies with a market focus, 16% address collective entities (public or communal users), and 18% also address nonagricultural land users. Almost 38% of papers examined more than one type of land users, owners, or managers. When collective users are involved, conservation and restoration of ecosystems are often investigated; see, e.g., the case of protected grassland management in Hungary (97) or wetland management in the Republic of South Africa (5). Much of the research does not specify the land tenure conditions of the study subjects, with more than 35% of papers referring broadly to land users without denoting ownership structure. This finding indicates a strong focus of research is on land modifications to support agriculture, with an emphasis on the private benefits of land modifications. It also suggests insufficient attention to how land tenure may affect decision-making.

The emphasis of the literature on small or subsistence-scale agriculture is reflected also in the types of land modifications examined. Articles identified in the systematic review most frequently focused on cropping alterations (63% of papers), followed by water capture and storage (49% of papers), soil enhancement (45% of papers), land cover alterations (42% of papers), and livestock alterations (30% of papers). Fewer articles addressed topographic alterations (25% of papers) or conversion of land use (26% of papers). Articles in the systematic review primarily address these land modifications in relation to their potential to reduce hydrologic risks to livelihoods, with much less attention to risk reduction for ecosystems, the built environment, or broader social systems. It is unclear whether the focus of the literature reflects the interests of researchers or realities on the ground. The review did not identify studies on interest in or availability of topographic alterations to small-scale and subsistence agriculturalists nor studies of whether and how small-scale and subsistence agriculturalists consider the potential of land modifications to produce public benefits.

5. MOTIVATIONS, BARRIERS, AND FACILITATORS TO IMPLEMENTATION OF LAND MODIFICATIONS

Implementation of land modifications will depend on the motivations of land owners, managers, and users and the ease with which they are able to undertake modifications should they seek to implement them.

5.1. Theories Explaining Behavior and Their Applications to Land Modification Implementation

A variety of theories explain human behavior and, while not developed to explain the motivation to undertake land modifications, provide useful frameworks for understanding human responses to risk and environmental stressors (98, 99). **Table 1** includes a list of commonly applied theories to the disaster risk mitigation behavior and a description of each. The theories differ in the exact details of how they conceptualize behavior yet share the presumption that behavior results from a

Table 1 Theories applicable to land modifications that explain human behavior

Theory and conceptualization of behavior	Factors influencing uptake of land modifications
Rational choice theory: Behavior is rational; people weigh the costs and benefits of alternatives and choose the option that best aligns with their personal preferences [first introduced by Smith (100); recent application by Pangapanga et al. (101)].	■ Costs of land modifications ■ Benefits of land modifications ■ Preferences for land modifications
Theory of planned behavior: Behavior is affected by personal attitudes, subjective norms, and perceived behavioral control [first introduced by Ajzen (102); recent application by Holt et al. (103)].	■ Attitudes toward land modifications ■ Social norms on land use and management ■ Perceived ease of implementing land modification ■ Perceived control over factors influencing ease of adopting land modification
Protection-motivation theory: Behavior is affected by a person's perceptions of risk and efficacy to mitigate risk by the individual action as well as by that person's capacity to take action [first introduced by Rogers (104); recent application by Milman et al. (23)].	■ Perceived risks of floods and droughts and perceived probability of their occurrence ■ Perceived efficacy of land modifications ■ Perceived self-efficacy to undertake land modifications (ability to take action)
(Focus) Theory of normative conduct: Behavior is influenced by social norms (what is normal, what is appropriate), as norms provide a decisional shortcut as to how to behave [first introduced by Cialdini et al. (105); recent application by Steg & Vlek (106)].	■ Social and cultural expectations regarding land management and use, including uptake of modifications ■ Relative salience of different norms in a certain context
Cultural ecology theory: Behavior is affected by both biological and cultural processes that enable reproduction and survival [first introduced by Steward (107); recent application by Ali (108)].	■ Physical and biological properties of the land ■ Risks of floods and droughts ■ Availability of technology ■ Adaptation capacity of individuals and communities
Value-belief-norm theory: Behavior is influenced by the intention to act derived from personal values, proenvironmental beliefs, and norms [first introduced by Stern (109); recent application by Moore & Boldero (110)]	■ Personal values (e.g., altruistic versus egoistic) regarding public and private benefits ■ Personal beliefs (worldviews, perceived ability to act) encouraging the action ■ Pro-environmental personal norms in relation to the land use and management of risks
Attitude-behavior-context theory: Behavior results from interaction among personal sphere attitudinal variables and contextual factors [first introduced by Stern & Oskamp (111); recent application by Okumah et al. (25)]	■ Internal attitudes (values, beliefs) toward land modifications and mitigation of risks ■ External context including behavioral standards and norms, incentives and costs, regulations related to adoption of land modifications

person's cognitive assessment of the effects and net benefits of actions, the risks of action/inaction, and personal and societal values and expectations. Examining across these theories and comparing findings from their application to land modifications is important for identifying which best explain differing actions and behavior (13) as well as for development of robust policies to guide human action (99).

Empirical evidence applying these theories specifically to land modifications is extremely limited. Only 4% of papers (4 total) identified in the systematic review explicitly theorize human behavior. Three of those papers draw on rational choice or protection-motivation theory to examine farming household-level preferences in relation to adoption of land modifications (50, 101, 112) while one draws on cultural ecology theory to explain trends in uptake of land modifications as part of the coevolution of human practices, the environment, and technology (108). The paucity of research theorizing behavior in relation to land modifications means there is a lack of knowledge regarding why those implementing modifications choose to do so and how motivations may differ by type of land user (e.g., private, collective, public), by sector (e.g., agriculture, forestry, urban), or by form of land modification (e.g., land cover alterations, soil enhancements, etc.)

Although the vast majority of the literature in the systematic review does not theorize the choice to deploy land modifications, a growing body of scholarly work that more broadly examines adaptation provides insights about human behavior in response to climate risks (13, 98). A prior synthesis of empirical studies on adaptation indicates action in response to climate change can be best predicted by self-efficacy (peoples' belief that they are capable of doing something), outcome efficacy (peoples' belief that an action will result in protection), negative affect (an unpleasant state of mind people wish to reduce), and descriptive norms (whether others adapt as well) (113). Moderating factors, such as type of climate hazard and form of adaptive behavior (113), as well as context (25) affect the relationships between beliefs, affect and norms, as well as which most drive action. For example, if an adaptation action is easy to undertake or does not incur significant behavioral or financial costs, cognitive factors, such as attitudes, have a greater effect on behavior; conversely, where effort and costs are higher, cognitive factors play a smaller role (110, 114).

Findings from the three aforementioned papers that examine household-level preferences for land modifications, along with several additional papers identified by the systematic review that examine the decision to adopt land modifications without explicitly theorizing behavior, align with findings from research on adaptation to climate change more broadly. These papers indicate that actors who perceive they have the capacity to take action (41, 112, 115); actors with greater education, knowledge, or access to training (50, 101, 112); and actors with greater access to resources, including wealth or technology (50, 112, 115), are more likely to adopt land modifications. With respect to how the personal characteristics of decision-makers influence the above, higher educational levels and greater experiences with farming make land users more likely to implement land modifications (54, 116). There is a lack of consensus regarding the role of age—elder farmers in Ethiopia were more likely to adopt soil enhancement and crop and livestock management alterations (117), and younger farmers in Thailand were more likely to undertake those same land modifications (54). Due to the paucity of captured evidence on the subject, how perceptions of self-efficacy, outcome efficacy, and negative affect relate to specific land modifications and whether they vary across private, public, and communal, as well as across large and small land owners, managers, and users, is unknown.

5.2. Barriers to and Enablers of Implementation of Land Modifications

As described in theories of human adaptation behavior, key to the decision of land owners, managers, and users to adopt land modifications are the contextual factors that create barriers and/or facilitate implementation of land modifications (25, 118). Even though it does not examine motivations for, the literature is rich with examples of barriers to and enablers of adoption of land modifications.

Barriers (also termed constraints or obstacles) are features emerging from the position of individual actors, the governance process of implementation, and the context in which the adaptation takes place that impede action yet can be overcome (118, 119). Barriers may be real, in that they are manifest in the external world, or may be perceived, in that they are part of an individual's mental processing in relation to the action. Barriers to adaptation to climate risks have been classified by a variety of scholars (see, e.g., 119, 120). Commonly identified categories include institutional, political, financial, cognitive-informational, cognitive-attitudinal, and physical barriers (see **Table 2** for definitions).

Thirty-one percent of papers (29 total) in the systematic review included some mention of barriers (see **Table 2** for details). Most frequently mentioned were financial barriers (22 papers), physical barriers (15 papers) and cognitive-informational barriers (13 papers). Institutional and

Table 2 Barriers to land modification implementation. Examples and respective citations include institutional: 116, 121 (Ahmad et al. 2021, Beckman & Nguyen 2016); financial: 41, 122 (Kalele et al. 2021, Jacobi et al. 2017); cognitive-informational: 41, 123 (Kalele et al. 2021, Maharjan & Maharjan 2020); cognitive-attitudinal: 43, 124 (Arora & Birwal 2017, Wu et al. 2013); and physical: 41, 125 (Kalele et al. 2021, Holden et al. 2018)

Barriers		Manifestation	Examples in systematic review
Institutional	Constraints due to the legal and normative processes governing land use and land use change, including the structure of and cooperation among oversight agencies and processes	• Insufficient support at and across levels of government • Unclear or insecure land tenure • Inadequate law enforcement	(11 papers mentioned in the systematic review) • Unclear land ownership reduces access to land and the long-term motivations of household farmers in Pakistan to adopt land adjustments (Ahmad et al. 2021). • Some villages in Vietnam cannot engage in replanting or agroforestry to address degraded forests because their village land certificates do not grant them rights to develop that land (Beckman & Nguyen 2016).
Political	Power dynamics and interests that impede decision-making or are opposed to implementation of specific land adjustments	• Political ideology • Instability or change of political representation	Not addressed in the systematic review
Financial	Constraints related to the economic and transaction costs of implementing land adjustments	• Low incomes • Limited access to credit • Opportunity costs of the land adjustment • Perverse incentives • Difficulty of selling agricultural products at local markets	(22 papers mentioned in the systematic review) • Limited access to credit and high cost of inputs (seeds, fertilizers, and pesticides) represent significant barriers to adoption of soil enhancements by smallholder farmers in Kenya (Kalele et al. 2021). • Agroforestry practices may reduce production of goods that could be sold at local Bolivian markets (Jacobi et al. 2017).
Cognitive-informational	Constraints related to insufficient knowledge and information on climate risks and land adjustments	• A lack of information and knowledge about climate change variability • Lack of awareness regarding feasible adaptation options	(13 papers mentioned in the systematic review) • Kenyan farmers lack information about higher yields provided by climate resilient and certified seeds (Kalele et al. 2021). • Nepalese land users have low awareness about climate change and its impact affecting their livelihoods (Maharjan & Maharjan 2020).
Cognitive-attitudinal	A reluctance to undertake land adjustments due to worldviews, values, or sociocultural pressures	• A lack of trust and willingness to cooperate among landowners/users • Social and cultural constraints to undertake land modifications	(10 papers mentioned in the systematic review) • Ethiopian farmers fear water capture and storage will bring unintended consequences, including local conflicts (Arora & Birwal 2017). • Some Chinese farmers who are good at paddy rice cultivation do not want to grow dry land crops (Wu et al. 2013).
Physical	Attributes of the property and natural conditions (geography, topography, spatial extent) that constrain deployment or effectiveness of land adjustments	• Shrinking labor force due to outmigration • Lack of or shrinking water availability • Degraded soil quality and quantity	(15 papers mentioned in the systematic review) • Poor and declining soil fertility leads Kenyan farmers to overuse chemical fertilizers rather than adopt land modifications that could address hydroclimatic risks, such as mulching (Kalele et al. 2021). • In Malawi, a lack of labor impedes adoption of labor-intensive conservation agriculture practices (Holden et al. 2018).

cognitive-attitudinal barriers were least frequently addressed (11 and 10 papers, respectively). Most of the barriers identified by papers in the systematic review are broad impediments to adaptation, irrespective of whether that adaptation includes land modifications (65, 76). Only one-third of barriers discussed were linked to a particular land modification. Financial barriers were primarily discussed in relation to soil enhancement and/or a lack of funds to purchase agricultural inputs for crop or livestock alterations (41, 122). Cognitive-informational barriers were frequently mentioned in relation to knowledge of new agricultural techniques for soil enhancement and crop alterations (123). Physical barriers were discussed most frequently in relation to land cover alterations, especially when constraints related to tree planting due to soil quality and water availability

Table 3 Enablers of land modification implementation. Examples and respective citations include regulatory/authority-based: 117, 126 (Teshager et al. 2014, Ahmad & Afzal 2020); economic: 125, 127 (Holden et al. 2018, Blackburn et al. 2018); information-based: 36, 51 (Rahut et al. 2021, Rolfe et al. 2021); and capacity building: 43, 36 (Arora & Birwal 2017, Rahut et al. 2021)

Enablers		Interventions	Examples from the systematic review
Regulatory/ authority-based 	Legal requirements for undertaking or changing regulations and administrative practices to make it easier to undertake land	• Strategic, catchment, or other land use planning • Formalization of property rights and land tenure reforms • Direct state interventions into land management practices	(9 papers mentioned in the systematic review) • Land ownership clarification would increase the willingness of land users to build irrigation canals in Ethiopia (Teshager et al. 2014), or to clean irrigation canals in Pakistan (Ahmad & Afzal 2020).
Economic 	Provision of financial or other resources to reduce the costs of or reward deployment of land adjustments or that increase a household's capacity to undertake land adjustments	• Access to credit, low interest loans • Subsidies • Payment for ecosystem services and other compensations • Development that improves livelihoods (diversified income, better linkages of products to markets)	(22 papers mentioned in the systematic review) • Subsidies reduced the cost of seeds, enabling farmers in Malawi to adopt crop alterations (Holden et al. 2018). • A payment for an ecosystem service scheme increased uptake of soil enhancements in North American rangelands (Blackburn et al. 2018).
Information-based 	Aimed at knowledge sharing and awareness raising	• Training workshops and programs • Demonstrations of specific technologies • Extension services • Awareness raising campaigns	(18 papers mentioned in the systematic review) • Training on climate-smart agriculture helps to modify existing farming practices in five African countries (Rahut et al. 2021). • Governmental knowledge exchange and advisory programs help Australian grazers adjust stocking rates and manage grazing practices to reduce their vulnerability to climate variability (Rolfe et al. 2021).
Capacity building 	Focused on social network development that results in both improved information transfer and strengthening of skills	• Knowledge sharing among neighbors • Support from or membership in trusted local organizations, such as farm associations and village groups • Active participation in consensus-building	(15 papers mentioned in the systematic review) • Pilots by a few risk-taking Ethiopian pastoralists who implemented water spreading weirs on their land served as an entry point to motivate other community members to adopt crop alterations and water capture and storage (Arora & Birwal 2017). • Membership in farm associations enabled African farmers to better use their networks to find production alternatives and led to broader adoption of soil alterations (Rahut et al. 2021).

(41, 125). Barriers delineated by papers in the systematic review are closely tied to the (aforementioned) emphasis of those papers on small-scale or subsistence agriculture in the Global South. Institutional barriers may be more prevalent in the Global North, where there are a greater number of institutions and regulatory processes governing activities undertaken on land (119, 128). Furthermore, with limited research for comparison, it remains to be determined whether financial, cognitive-informational, and cognitive-attitudinal barriers between small private (and predominantly agricultural) land users and public, collective, or larger-scale land users differ.

Enablers (also termed facilitators or drivers) are external interventions that can help to overcome barriers to and otherwise support implementation of land modifications. Such external interventions may be undertaken by a variety of entities seeking to encourage adoption of land modifications, including public agencies and nongovernmental or even private organizations. Categories of enablers commonly include regulatory- and authority-based, economic-based, information-based, and capacity-building enablers (see **Table 3** for definitions).

Almost 40% of papers (37 total) in the systematic review addressed enablers. The most frequent categories addressed were economic enablers (22 papers), followed by information-based enablers (18 papers), capacity-building enablers (15 papers), and regulatory enablers (9 papers).

Unlike how the literature approaches barriers, scholars more closely link enablers to specific types of land modifications. Articles in the review suggest land cover and livestock management alterations are equally supported by all four types of enablers (38, 122); soil enhancement and crop alterations are best enabled by economic, information-based, and capacity-building enablers; and water capture and storage is best enabled by regulatory- and authority-based interventions. The literature includes little discussion regarding enablers of land topography alterations or conversion of land use.

In terms of how enablers relate to specific barriers, financial barriers can be addressed to a large extent by economic enablers (such as rewards, subsidies or direct provision of material) (125, 127), although some financial barriers, such as outmigration/lack of labor, are caused by overall macroeconomic trends that are difficult to reverse. Cognitive-informational and cognitive-attitudinal barriers can be addressed by information-based and capacity-building enablers (43, 51). Institutional barriers can primarily be reduced by regulatory- and authority-based enablers such as land tenure reform or better law enforcement (117). Fewer enablers address physical barriers. Some physical barriers can be enabled by economic enablers such as public investments in infrastructure or regulatory- and authority-based enablers such as land tenure reform. However, in other instances, physical barriers may preclude adoption of a particular land modification on a particular plot of land.

6. ASSESSMENT OF IMPACTS AND EXPANDING DEPLOYMENT

While land modifications portend promising mechanisms for responding to the concurrent occurrence of flood and drought risks, the extent to which land modifications can serve to reduce hydroclimatic risks at the plot level and beyond remains a critical question. Answering this question requires two steps: (*a*) identifying and quantifying the actual risk reduction that occurs from implementation of land modifications at the scale of an individual project, at larger scales, and as multiple land modifications accrue across the landscape, as well as (*b*) determining the extent to which land modifications are feasible and likely to be widely implemented.

6.1. Quantifying the Benefits of Land Modifications

Under some circumstances, quantification of the expected benefits from land modifications is not needed for implementation. For example, decision-makers may not need detailed knowledge of the effects of land modifications when cobenefits—such as environmental protection or livelihood enhancement—drive the decision to change land use (55, 129), when land modifications reflect so-called no-regret strategies (21), or when land modifications are adopted because they are perceived as the right thing to do (75, 130). In other instances, quantification of expected impacts is important for the decision to implement the land modification. For example, many public agencies are required to engage in evidence-based policy-making (see, e.g., 131), and thus public agencies that manage land or public agencies creating policies to encourage implementation of land modifications may need to demonstrate proof of effectiveness in order to support land modifications.

Delivering robust evidence for land modifications for hydroclimatic risk mitigation is complex. The impacts of land modifications will depend on a variety of factors including the physical extent of the modification, its geographic location, and site-specific details (6, 10, 30). For example, the flood risk mitigation benefits of water capture and storage and land topography alterations depend on size of the catchment, the stream network, as well as the location and the design of the land modification (6). As another example, the water retention capacity of land cover alterations such as reforestation depend on vegetation characteristics, soil porosity and depth, elevation, and slope

(106, 132). In some instances, the length of time a modification has been in place also affects the benefits it provides. For example, the type of vegetative cover and its extent of coverage impact runoff (133, 134), yet vegetation takes time to grow to its full size. Benefits of land modifications may also vary under differing hydroclimatic conditions. Many land modifications work well for small- or medium-magnitude events (e.g., the 10-to-20-year or even 50-year flood), but not for extreme flooding. Effectiveness will also depend on recent hydroclimatic conditions. For example, the extent to which forests in headwater catchments reduce the peak of flood events varies between 3% and 70%, in part due to pre-event soil moisture (134).

Evaluating and quantifying the effects of land modifications requires detailed monitoring and tracking of water flows and soil conditions over an extended period, including across regular variation in weather conditions. Most land owners, managers, and users implementing land modifications do not undertake such detailed monitoring (11, 75). Furthermore, while many public agencies, such as watershed authorities or natural resource agencies, have monitoring responsibilities, political, economic, human-resource, and bureaucratic factors constrain the extent of monitoring they are able to engage in (135). Given the emphasis of papers captured within the systematic review on the Global South, monitoring capacity constraints may explain why few quantify the hydroclimatic risk reduction benefits of land modifications.

With respect to evidence beyond the papers identified in our systematic review, a 2020 systematic review of the scientific literature of nature-based solutions found that while there is evidence of the biodiversity enhancement benefits of nature-based solutions, including land modifications, evidence is missing on mitigation of hydroclimatic risks (136). The very few instances of detailed research on the effects of land modifications address a single modification or small-scale deployment. For example, research in Scotland calculated that temporary storage ponds with 200 to 2,000 m^3 of retention capacity on fields within a 4 km^2 catchment area can reduce the risk of flooding by 30%. Furthermore, as those ponds retain storm water for only 12–24 hours, they do not reduce farmland productivity. A study also showed that if sediments detained in storage ponds are removed, temporally storage ponds provide the cobenefit of mitigating soil erosion (4). Similarly, rock check dams in Arizona were shown to increase groundwater recharge and promote stable surface water runoff (137).

Analysis of the effects of land modifications at a larger scale and within larger catchments (i.e., exceeding the extent of 10 km^2) also does not appear in the systematic review, although scientists have researched effects in greater detail. Such studies generally rely on simulations (134) or a comparison of measured runoff changes before and after an intervention (137) rather than detailed monitoring of flows throughout the catchment. A considerable amount of research has utilized computer modeling to examine how land modifications such as development and urbanization increase hydroclimatic risks throughout a watershed (see, e.g., 138, 139). The past decade has seen a flip in that paradigm, with use of computer modeling to evaluate the potential for land modifications to reduce rather than increase hydroclimatic risks (see, e.g., 140, 141) as well as to identify locations where land modifications could be implemented to reduce hydroclimatic risks (see, e.g., 142). Computer modeling is particularly useful for estimating the magnitude of the effects of larger-scale land modification. However, computer modeling has limitations, especially where data on land cover and hydrogeologic conditions are sparse or at a coarse scale. Local conditions affect flows throughout a catchment yet, without substantial data for calibration, many models must rely on broad simplifications and assumptions to represent the physical conditions in the catchment.

While analysis of the potential risk reduction benefits from increased deployment of land modifications is important, small variations within the landscape may mean attempts to generalize from small plots to catchments may lead to inaccurate conclusions (14). Watersheds also have emergent properties, meaning functioning at higher-order scales (e.g., the broader catchment) cannot be fully determined by components at lower scales (e.g., subcatchments or individual parcels) (143). Furthermore, uncertainty related to translating expected changes in regional climate into localized impacts complicates the evaluation of measures (144).

6.2. Expanding Implementation

The degree to which land modifications contribute to hydroclimatic risk reduction will also depend on the extent to which they are implemented. Expanding deployment of land modifications will require overcoming the barriers to deployment described above. Papers in the systematic review specifically identify cognitive-informational, financial, institutional, and political barriers to widespread deployment of land modifications. With respect to cognitive-informational barriers, scholars assert broadening the extent to which land modifications are deployed will require greater knowledge of the factors influencing adoption of land modifications (52, 145) and greater dissemination of information on land modifications as an option (41). Mismatches exist between the coarse scale of information on climate change, and the localized information needs of the land users who may adopt land modifications also need to be resolved (146). Solutions proposed in the literature include extensive capacity building and knowledge transfer (41) along with downscaling and dissemination of information on climate change (146, 147).

Financing is also described by articles in the systematic review as a substantial barrier to widespread deployment of land modifications. Investments in large-scale land modifications are missing (44) and financial constraints impede increased deployment of capital-intensive land modifications (148). Research shows high investment costs make small-scale farmers hesitant to engage in large-scale crop or livestock modifications (96). Furthermore, time-scale mismatches occur between when small-scale farmers have resources available (the end of a season) and when decisions to embark on crop or livestock modifications ensue (44, 147). Subsidies and the creation of ecosystem service markets have also been used to promote soil enhancement and crop modifications (125, 127).

The literature addresses institutional and political barriers to expanded deployment of land modifications with less detail. One paper in the systematic review discusses the need for cooperation, joint planning, and participatory engagement as well as support from higher levels of government (45); another highlights that much of the research on land modifications describes the behavior of actors at the local scale, yet decision-making regarding land modifications is affected by political decisions at the national scale and by global market dynamics on the international scale (149). The relatively minor attention by papers in the systemic review to expanding deployment of land modifications is due to the fact that most of the research adopts the households or individuals as the unit of analysis without little consideration of the broader context in which land modifications may be implemented.

Even though there is less attention in the extant literature to institutional and political barriers to more widespread deployment of land modifications, those barriers are likely highly important. For land modifications to be deployed to the extent necessary to bring about watershed-scale effects, land modifications will either have to be deployed on a greater number of parcels (scaling out) or at a larger magnitude (scaling-up). Whether efforts to overcome cognitive-informational and financial barriers are successful will in part depend on how those efforts are perceived and experienced by a wide variety of actors. Coordination and potentially cooperation between actors may be needed for scaling-up and will be essential for implementing in locations that maximize collective benefits, yet such coordination and cooperation will depend on actor willingness to undertake land modifications due to the public benefits they provide.

7. LOOKING FORWARD: PROSPECTS, KNOWLEDGE NEEDS, AND FUTURE RESEARCH

Our review of the state of knowledge on land modifications to jointly mitigate the risks of both floods and droughts and the people who make decisions regarding their implementation indicates that although scholarly work has begun to address this topic, with 93 peer-reviewed Scopus and Web of Science articles meeting our selection criteria, substantial gaps in knowledge remain regarding human preferences, behaviors, and the potential for expanding deployment.

First and foremost, the literature does not address well the use of land modifications to contend with climate variability. Many land modifications have the potential to serve the dual purpose of mitigating risks stemming from both too much and too little water. Consequently, a search criterion for the systematic review was that papers must include reference to the risks of both floods and droughts. While all of the papers identified in the systematic review included some reference to both hazards, only a few explicitly addressed the ways in which land modifications were concurrently addressing them (see, e.g., 37, 43, 44). The papers also do not examine whether and how land owners, managers, and users evaluate and make decisions based on both potential risks. Rather, even though all of the papers identified by the systematic review referenced both floods and droughts, the papers either tended to emphasize only one of the two hydroclimatic risks or focused more vaguely on adaptation to climate change, without connecting the land modifications with risks in detail (36, 39, 48). Given the need to recognize the effects of compounding and cascading risks (150), much greater attention to the potential for land modifications to serve multiple purposes and to the ways in which actors perceive and act on land modifications as a response to concurrent risks is needed.

Second, a majority (>86%) of the papers identified in the systematic review encompass evidence on land modifications from the Global South. This trend is noteworthy because there is often a bias in the English academic literature toward evidence on the Global North, particularly on environmentally related topics (see, e.g., 136). That many articles address land modifications in the Global South likely reflects major concerns of researchers, and funders of research, regarding the fate of low-income households in relation to climate change. Such concerns are also evidenced by the fact that many of those papers examine adaptation quite broadly, with land modifications considered in the research as only one among many alternatives to address livelihood and food security under a changing climate (54, 145, 148). The result is that while the literature provides a fairly robust depiction of general motivations of, as well as barriers to and enablers of, action by households in the Global South, it does not provide nuanced understandings of household perspectives on joint reduction of flood and drought risks nor on differences across types of land modifications.

Importantly, there are prominent differences in the framing of the literature on actors and land modifications in the Global South versus in the Global North. The narrative within much of the literature on the Global South focuses on the risks posed by climate change in areas already facing food insecurity due to constraints on land productivity, technology, and resource availability (41, 45). Vulnerability of livelihoods to hydroclimatic events is a central concern for which land modifications represent a potentially affordable solution that simultaneously contributes to economic development (see, e.g., 55, 95). In contrast, the narrative conveyed in the literature on the Global North focuses on the impact of historic land use change and the services provided by ecosystems (see, e.g., 44, 96). Here, the argument depicts the value of multifunctional landscapes as much in relation to mitigating hydroclimatic risks as in relation to supporting ecosystems restoration/resilience. The difference between the two narratives likely explains (*a*) the aforementioned emphasis of literature on land modifications in the Global South by subsistence-scale or small-scale agricultural households, and (*b*) the relative dearth of papers from the Global North that met the criteria for the systematic review. Even though there is a relatively large literature on nature-based solutions and natural flood risk management in both Europe and the United States (see, e.g., 24, 136, 151), the few that consider land modifications to jointly mitigate floods and droughts do not include the role of land owners, managers, and users.

Because the literature in the systematic review predominantly focuses on small- or subsistence-scale agriculture in the Global South, information about land modifications for larger-scale productive uses and by actors in other (e.g., forestry, recreational, residential, or urban) sectors is lacking. Our understanding of deployment of land modifications by public entities, collectives, and users of larger parcels of land is especially limited (see, e.g., 97, 149). This gap is problematic, for a variety of reasons. First, while agriculture land use (grazing and crops) jointly comprises 37.6% of global land use (152), 84% of farms are small (less than 2 ha), and these small farms operate on only approximately 12% of global farmland (153). As public, collective, and/or large land owners, managers, and users can implement land modifications at a larger scale, and thus the potential effects of those modifications at the watershed level are larger, those actors merit greater attention. Second, the context in which public, collective, and/or large land users engage in land modifications differs from that of small- or subsistence-scale agriculture and pastoralism, and thus findings from one type of actor may not be transferrable to others.

Furthermore, because much of the literature in the systematic review is concerned with climate adaptation and risks to livelihoods with the household as the unit of analysis, there is little information on how land managers, owners, and users perceive land modifications in relation to other types of risks, such as the effects of floods and droughts on buildings, infrastructure, health, and ecosystems. Perceptions and/or evaluations of the potential public benefits from land modifications are rarely examined (see, e.g., 38, 84).

Also absent across the literature on both the Global South and Global North is theorizing in relation to the motivations and decision-making processes of people in relation to implementation of land modifications. While existing research identifies barriers to and enablers of land modifications (41, 48, 49), very few papers examine the question of why differing actors might be interested or willing to adopt land modifications (101, 112). Overall, the literature employs the implicit assumption that land users will adopt land modifications if they both perceive a climate risk and have the capacity to implement the land modification (41, 123, 126). However, as we know from a long tradition of scholarly work on risk protection and environmental behavior, people weigh multiple factors when making decisions about what actions to undertake (23, 25, 98). For implementation of land modifications to become widespread, we need to develop much deeper understandings of how people perceive land modifications, what drives their decision-making process, and the influence of the social and institutional structure in which land users are embedded on their decision-making process.

Particular attention to determining the knowledge requirements of land users as they engage in deciding whether to deploy land modifications is needed, and how those requirements vary by actor and by type of land modification. As described above, frequently the effects of land modifications are not monitored and ex ante quantification of the benefits of land modifications is not undertaken. Without understanding the knowledge needs of the multiple actors involved in land modification, scholars, practitioners, and even project designers cannot produce the data and information necessary to support land modification decisions, let alone deployment.

It is also essential to improve understandings of the social psychology regarding how land users consider the private versus public benefits of land modifications (75, 78). Benefits from land modifications may accrue to entities in the watershed beyond the implementer. For example, upstream water retention can reduce both downstream flood risk and the effects of future dry periods where the water is retained (4, 45). Literature identified in the systematic review primarily focused on private benefits and did not address how actors weigh the distribution of private versus public benefits of land modifications. Improved understandings of the perspectives and motivations of actors in relation to the public versus private benefits of land adjustments, and how those are related to social institutions and decision-making, are needed to identify the full range of barriers to land modification as well as to determine the potential for interventions to steer uptake of land modifications.

Lastly, we need to more thoroughly identify the barriers or enablers that are specific to each type of land modification and each context for implementation. Each type of land modification may have a different interaction with land tenure practices as well as with laws, regulations, and societal expectations related to land, water, and the environment. Some land modifications are more permanent than others. Even though there are many similarities and shared characteristics, it is important to distinguish between land modifications, as some may be more well suited or feasible for certain situations than for others.

Land modifications are a potentially valuable tool for adaptation in regions that concurrently face the prospect of future floods and droughts. In addition to mitigating hydroclimatic risks, many land modifications can provide ecological and economic cobenefits. Further attention to the intersecting human and physical dimensions of land modifications is needed to evaluate their full potential as well as ensure they receive full consideration on the adaptation agenda.

SUMMARY POINTS

1. Modifications to land characteristics, use, and management can serve to jointly mitigate the risks of both floods and droughts. Land modifications reduce risks by intervening in the hydroclimatic conditions in ways that slow flows, infiltrate water, reduce runoff, and/or store water. Land modifications can also serve to reduce demands for water or the sensitivity of production to variability in rainfall.
2. Seven types of land modifications include land cover change, soil enhancements, topographic alterations, water capture and storage, cropping alterations, livestock alterations, and conversion of land use.
3. The geographic expanse and specific location of land modifications affect whether they have property-level, localized, or watershed effects. How land users weigh off-property effects when making decisions regarding land modifications has not been well explored.
4. Most of the research on land modifications to address concurrent risks of floods is focused on the Global South. Research located in Asia and Africa primarily examines small-scale (subsistence) farmers, whereas research in North America and Australia addresses a broader range of land owner, manager, and user types, including communal schemes, private companies, and nonagricultural users.
5. Land owners, managers, and users are heterogeneous, with differing needs, preferences, and capacities. Due to limited empirical evidence for comparison, it remains to be determined whether motivations for and enablers of/barriers to implementation vary across small private (and predominantly agricultural) land users and public, collective, or larger-scale land users.

6. Literature focused on land modifications in the Global South frames the hydroclimatic mitigation challenge mostly as related to livelihoods, whereas literature on land modifications in the Global North emphasizes a socio-ecosystem resilience narrative.
7. Most studies do not theorize behavior of land users, and few studies provide in-depth examination of motivations to deploy specific types of land modifications for mitigating concurrent flood and drought risks.
8. The effect of enabling strategies varies across types of land modification. Land cover and livestock management alterations are equally supported by all forms of enabler; soil enhancement and crop alterations are best enabled by economic, information-based, and capacity-building enablers; and water capture and storage is best enabled by regulatory- and authority-based interventions. The literature includes little discussion regarding enablers of land topography alterations or conversion of land use.

FUTURE ISSUES

1. Despite a well-recognized need to address compound and cascading risks, research on land modifications neither delves into detail regarding the potential for land modifications to concurrently mitigate the risks of floods and droughts nor addresses how land owners, managers, and users perceive and are motivated by dual versus single risks. Deeper examination of the potential for land modifications to serve multiple purposes and how actors view this multifunctional aspect of land modifications will be useful for informing the future policies and programs aimed at risk mitigation.
2. The potential contributions of land modifications to mitigation of concurrent flood and drought risks, as well as barriers and motivators to their deployment, will be influenced by geographic, ecologic, and socioeconomic factors. Comparative research is needed to understand the physical effects of land modifications across biomes as well as how the social contexts influence deployment.
3. Land users have multiple options in choosing what land modifications to deploy and are not constrained to deployment of a single modification. Furthermore, as deployment expands within a catchment, the effects of land modifications may change. Greater understanding is needed of the potential trade-offs across types of land modifications, across locations of land modifications, of interactions between land modifications, and of the cumulative effects of multiple land modifications. Such information can be used to provide guidance, raise awareness, and produce decision-support tools to aid land users in decision-making.
4. While it is well recognized that land modifications have the potential to provide both public and private benefits, the willingness and interest of land owners, managers, and users to consider public benefits as they make decisions about land modification implementation is not known. Insights on how actors making decisions to implement land modifications weigh public benefits may help in the development of enabling policies seeking to convince those actors do implement land modifications on their lands, especially land modifications intended to achieve watershed-scale effects.

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